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Yield Stress Analysis With DV-III Rheometer

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YIELD STRESS ANALYSIS WITH DV-III RHEOMETER

by
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ABSTRACT

The purpose of this thesis is to understand the behavior of everyday substances (toothpaste, lotions, ect.) and chemicals through the analysis of yield stress. By measuring the flow properties of these products, one can determine the stability, uses, and other properties of a substance. Yield stress is experienced everyday from squeezing a tube of toothpaste, to stirring a batch of cake batter, or canning products in a factory. Yield stress along with viscosity helps us predict the behavior of chemicals, cosmetics, and food that we handle daily.

Yield stress, torque, and strain values were measured with a DV-III Rheometer and the EZ Yield software. These values were graphed using Logger Pro and Microsoft Excel to demonstrate the trends of these values and the differences of them between each sample. For example, the stress verses strain graph represents a sample's elastic energy, plastic energy, and point at which this transition occurs. Although not measured in this paper, when metals are graphed on this curve it can provide characteristics such as the degree of brittle or ductile behavior (4). Another useful graph is showing the fluidity of a sample by using its viscosity measurements. Samples that lose flow resistance with increasing heat result in a negatively sloped linear graph on an inverse log plot.

Comparing yield stress between similar polymers and different brands of mayonnaise showed an unseen difference in products of seemingly identical composition. Other comparisons can show the difference in the behavior of Newtonian, non-Newtonian, and other categories of substances.

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LIST OF ABBREVIATIONS

K	Consistency
n	shear thinning index
PEG 350	Poly (ethylene glycol) , Molecular Weight 350
PEG 750	Poly (ethylene glycol) , Molecular Weight 750
RPM	Revolutions Per Minute
S	Radial Spring Factor (rad/ % torque)
η	Viscosity
τ	Yield Stress (Pa)
T_k	Model Torque Constant
θ_M	Angular Rotation (rad)
σ_0	Yield Stress
T	Percent Torque (%)
γ	Strain (rad)

INTRODUCTION

The viscosity of a substance helps determine its possible uses, its efficiency, and its durability. Knowing these values is essential for many industrial evaluations especially in food and cosmetic industries. In relation to viscosity, yield stress values show a material's strength, which allows better understanding of its performance as well as its stability and its energetic absorbance. Yield stress measures the amount of force required to initiate flow of a substance, which can be affected by temperature, consistency, rate of rotation, time, and viscosity. Stress refers to the force exerted and yield is the point where shape change begins to occur. Typically, higher yield stress indicates a more consistent fluid that is less inclined to separation or phase change. Having too low of a yield stress would allow the substance to spill out of its container with no force at all; however, having too high of a yield stress would require the consumer to exert a great deal of force in order to expel the substance. Manufactures have to pay great attention to this property to determine distribution and shipping methods because gravity, shifting, and vibrational forces the products will encounter (9). Finding the perfect balance of stress is necessary for producers wanting to maximize the efficacy, shelf life, and overall applicability of a product.

The yield stress of a substance can be obtained from a double logarithmic plot of viscosity versus stress. This method for yield stress is performed automatically by Brookfield's program, EZ Yield. This program controls the DV-III Ultra Rheometer and its vane spindles, which measures the torque applied to a material at various speeds. The vane spindles differ in size and shape, which determines the shear stress of a substance. The largest vane spindle, 71, is used for materials that are quicker to initiate flow to give a larger torque value and is more accurate for low yield materials. The smallest vane spindle, 73, is used for materials that require more force to exhibit flow, so as to not exceed the maximum torque value for the instrument. Depending on the properties of the material, some of the spindles may not be able to provide a yield stress, so it is important to use the best-matched spindle for the torque required for each substance. When using vane spindles to measure yield stress, the speed must be between 0.01 and 5.00 revolutions per minute (RPM). The maximum torque value experienced by the spindle is the yield point, which in relation to time gives a yield stress value.

EZ yield also measures strain, which is shown as the rate of deformation of a substance. This value demonstrates the structural behavior of a product when a force is present. When using this equipment, torque readings need to read between 10% and 100%, in order to obtain valid data. Torque reduction is generally always set at 100%, which ends the test once there is no more increases in torque. Throughout this study, all tests were set at 100% torque reduction. Because temperature can affect the yield stress of a substance is important, all yield stress tests were measured at room temperature in order to eliminate an influencing variable. For a substance that is too fluid, a yield stress value may not be able to be obtained with this equipment because it is under the minimum torque for a reliable measurement, even with the largest spindle.

There are many methods for analyzing yield stress. The Steady State Stress Sweep is typically used on materials with medium viscosity, and the torque is graphed logarithmically in increments until the yield stress is reached (9). This method is dependent on how many data points are graphed, and is used usually the most common method. Another method is the Steady Rate Sweep method, which is used for low viscosity materials (9). This method is generally easier to find the yield stress value, and is measured using the cone and plate device. One more method is the Dynamic Stress/Strain Sweep Method, which is used for highly viscous samples. In such samples, the problem of slippage can occur making data hard to obtain or give lower, inaccurate measurements (9). Using the cone and plate mechanism, this method allows the data to be graphed as a double logarithmic plot with oscillation stress (9).

Before conducting tests on each material, knowing whether or not the substance was a Newtonian fluid or a Non-Newtonian fluid was helpful in predicting how the sample would behave. A Newtonian material is one that has a consistent viscosity depending on the shear stress, and it creates a linear graph of shear rate verses shear stress (9). A non-Newtonian material experiences changing viscosity based on the applied stress, and its graph results in a shear thinning or shear thickening curve (9). Shear thinning occurs when a fluid's viscosity decreases with increasing rates of velocity or stress (11). Some examples of this behavior are ketchup and paint. On the other hand, shear thickening occurs when a sample's viscosity increases with higher velocities or stress. At rest, a material that exhibits shear thickening will have its particles randomly scattered with limited interaction between these particles. Once it is flowing, these particles become more compact. Shear Thickening materials have a high stress value when high velocity or force over a short distance is applied, making its structure act more as a solid than a liquid. This property is rarely observed, and may indicate a material's instability (11). This change in the linear proportion is due to the deformation of the material caused by the stress exerted. In most cases, samples will not display Newtonian behaving materials will have a yield stress graph that goes into a plateau after the yield point has been reached (11). However, very few substances are entirely Newtonian. Thus, knowing the yield stress values can allow producers to strengthen their products by increasing their yield stress value. While yield stress values are useful, this value is not present in all materials and is best suited when analyzing complex substances such as grease, pastes, emulsifies, and paints (9).

A common way to analyze yield stress is by using a model to fit the Stress curve of a sample. One such model is the Casson Model, which typically is used for Newtonian substances that are visco-elastic fluids (12). Another model, which was discussed earlier, is the Bingham Model. This model is generally simpler than the others, and it describes Newtonian liquids with suspended particles (11). If the stress versus shear rate curve plots a line with a positive slope throughout the entire graph, a Bingham fit line could be graphed through this curve. At the intersection of these two lines, the Y values would be the yield stress value of the sample. For describing non-Newtonian functions, the Herschel-Bukley Model is used. The stress- shear rate curves for this model and for the Bingham model are similar; however, the Bingham model has a linear trend while the Herschel-Bulkley Model resembles a logarithmic curve (12). The equations of each model are provided below.

$$\sqrt{\sigma} = \sqrt{\sigma_0} + \sqrt{\eta_C \dot{\gamma}}$$

Formula 1: Casson Model

$$\sigma = \sigma_0 + \eta_B \dot{\gamma}$$

Formula 2: Bingham model

$$\sigma = \sigma_0 + K\dot{\gamma}^n$$

Formula 3: Hershel-Bulkley Model

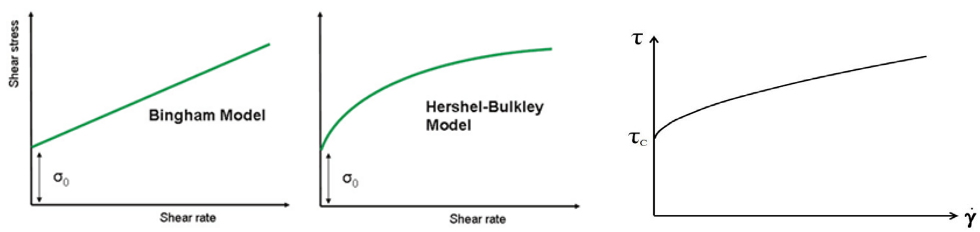


Image 1: Bingham, Hershel-Bulkley, and Casson Model

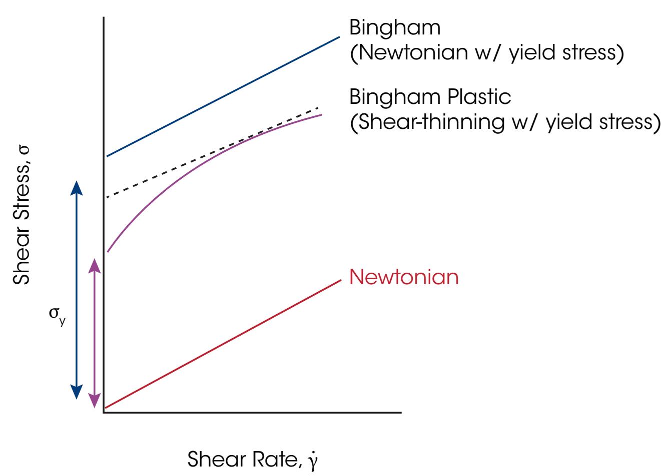


Image 2: The graph shows how materials' yield stress values should ideally act, but the actual values depend on other unaccounted forces and properties of a substance. Therefore, we typically refer to measured yield stresses as the apparent yield stress. On this stress verses rate plot, a Newtonian material, Bingham plastic material, and a Bingham Newtonian Material are graphed (9).

Another function of yield stress values is using them to compare similar products and chemicals, such as different brands of the same product or different versions of the same polymer. To a naked eye the related products may seem almost identical in texture, the yield stress values could prove to be very different. Rheology, or the study of deformation and flow of a matter (5), is helpful in determining properties of materials and understanding how they behave.

METHODS

In order to conduct this research, an AMETEK Brookfield DV-III Ultra Rheometer was used along with a cone spindles 40 and 52 with a cup and vane spindles 71, 72, 73. This instrument allowed for the measurement of viscosity and the prediction of substance's flowing ability. Viscosity is measured in centipoise (cP), which is also the SI unit of milliPascal-seconds. Brookfield's accompanying computer programs including EZ-yield were used to collect yield values using the vane spindles (2). There are two immersion marks on the vane spindles, which can affect the stress values. The primary mark is higher up on the spindle shaft, while the secondary mark is located in the middle of the blades. Normally, the primary immersion mark is used, but because not all materials could reach this point, all data was collected using the secondary immersion mark. Spindle 73 is the smallest and is used for the denser samples. Spindle 71 is the largest and is better suited for substances that do not require as much torque to initiate flow. The cone spindles 40 and 52 were only used to obtain the viscosity of each substance. Spindle 52 is better suited for samples of higher viscosity and does not require as much of the sample (3).

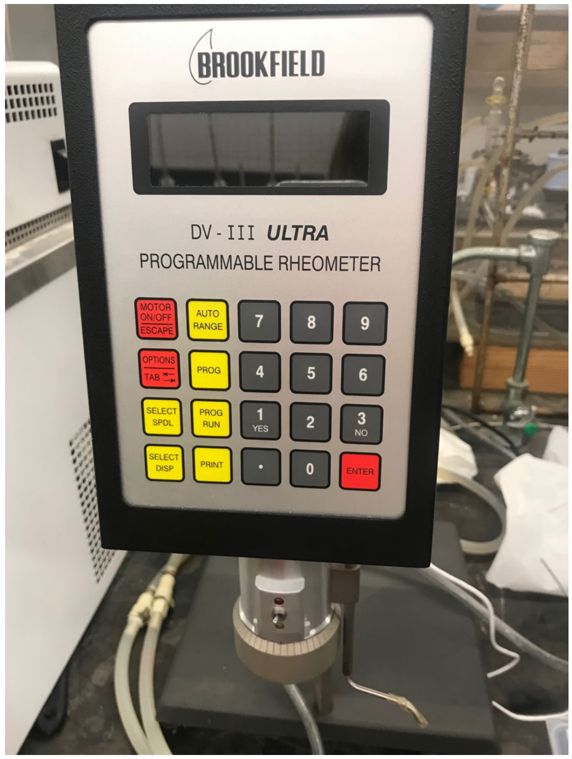


Image 3: This is the DV-III Ultra Rheometer used to obtain viscosity and yield stress values throughout this project. A graphics Series GS790 computer with the EZ Yield program was attached and collected the data.

Image 4: These are the pieces that attach to the rheometer for the cone and plate mechanism. The far left cup holds the liquid being measured and snaps into the rheometer. The two pieces on the right are the cones that attach to the instrument's drive shaft. The middle piece is the 40 spindle, which is used for less viscous samples, and the far right piece is the 52 spindle.

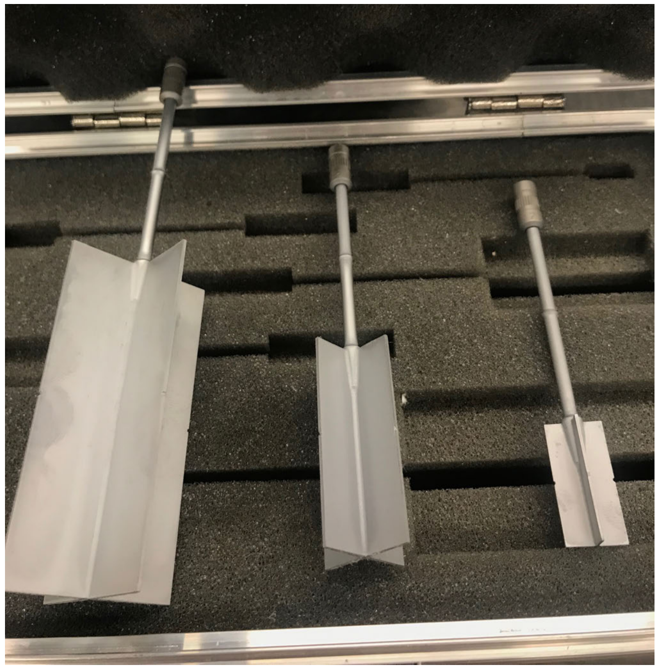


Image 5: These are the three vane spindles that screw into the rheometer and can be directly entered into the sample. The far left is spindle 71, followed by spindle 72, and spindle 73 on the far right.

For all yield stress test, torque reduction was set to 100%, meaning that the test would end once there was no increase of torque in a base increment. This setting allowed the yield point to be collected and extending this parameter would give a decreasing torque value.

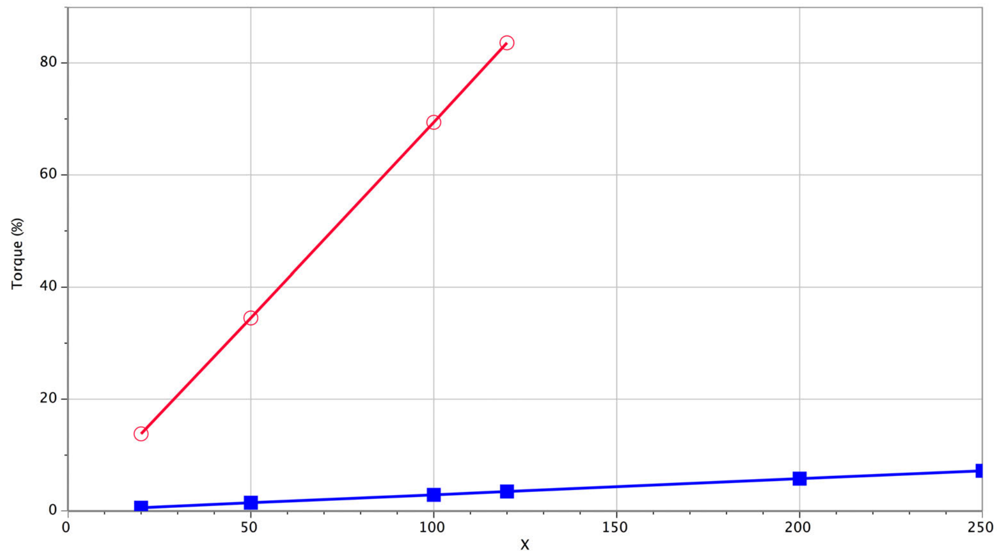


Image 6: Cone Comparison. The blue line is spindle 53 and red is spindle 40. The X axis is RPM and Y axis is torque. The material used is PEG 500, and when using the 40 spindle, the torque almost reaches 100% by an RPM of 120.

As seen in image 5, the size of the spindle gives readings of vastly different torques with the same sample. The 40 spindle is much larger in diameter, with more sample contact, and requires more torque even at slower speeds. The 52 spindle has a much smaller diameter, thus does not experience as much torque, and is normally used for more viscous materials. This is because the larger spindle participates in more shearing on the sample. The average viscosity of PEG 500 measured with spindle 40 was 46.5 cp. However, the average viscosity of the same sample but measured with spindle 52 was 52.3 cp. These values are still very similar, but the spindle size caused the readings to be slightly different. Because the viscosity values change with different forces applied, it can be inferred that PEG 500 behaves in a somewhat Non-Newtonian manner.

Torque is shown as a percent and is measured in Dyne-centimeters (10^7 Dyne•cm) or Newton-meters (N•m). The stress measurement at this final point is the yield stress value, which is measured in Pascals (Pa). The yield stress can be calculated using the following equation, where τ is the yield stress, T_k is the Model Torque Constant (3), T_{MC} is the Yield Multiplier Constant (3), and T is the percent Torque.

$$\tau = \frac{T_k \cdot T_{MC} \cdot T}{10}$$

Formula 4: Yield Stress Formula

The EZ Yield program also measured the strain, which was shown in units of radians. The strain is the angular distance that the spindle rotates in the substance. Strain rate is the rate of deformation of the substance when force is applied. The following equation can be used to obtain strain measurement:

$$\gamma = \theta_M - (S \times T)$$

Formula 5: Strain Formula

Torque was presented as a percentage, but its units are Newton meters or dyne-centimeters. Torque values varied depending on the substance, spindle, and speed. If the torque value was too low, increasing the speed or using a larger spindle would increase the torque.

Data was taken and graphed of household items including Suave advanced therapy lotion, Equate Beauty Pink Grapefruit facewash with microbeads, Colgate toothpaste, Equate baby Petroleum Jelly and Cra-Z-Art Washable kids paint. Poly ethylene glycol, or PEG, with molecular weights of 350 and 750 were also tested. The ingredients of the lotion were water, glycerin, stearic acid, glycol stearate, glyceryl stearate, triethanolamine, isopropyl palmitate, cetyl alcohol, dimethicone, petrolatum, magnesium aluminum silicate, fragrance, DMDM hydration, carbomer, disodium

EDTA, methylparaben, iodopropynyl butylcarbamate, stearamide AMP, tocopheryl acetate, retinyl palmitate, helianthus, annuus seed oil, and titanium dioxide.

The ingredients of the face wash with microbeads included active salicylic acid 2.0%, water, Sodium C14-16 Olefin Sulfonate, Glycerin, Cocamidopropyl Betaine, Acrylates Copolymer, Sodium Chloride, Stearyl Stearate, Euphorbia Cerifera (Candelilla) Wax, Jojoba Esters, Carrageenan, C12-15 Alkyl Lactate, Disodium Edta, Cocamidopropyl Pg-Dimonium Chloride Phosphate, Citrus Grandis (Grapefruit) Fruit Extract, Polyquaternium-7, Camellia Sinensis Leaf Extract, Ascorbyl Palmitate, Neopentyl Glycol Dicaprylate/Dicaprate, Anthemis Nobilis Flower Extract, Polysorbate 20, Polyvinyl Alcohol, Propylene Glycol, Benzalkonium Chloride, Butylene Glycol, Sodium Benzotriazolyl Butylphenol Sulfonate, Agar, Mica, Titanium Dioxide, Sodium Hydroxide, Fragrance, Citric Acid, Red 30, Red 40, and Violet 2.

The ingredients of the toothpaste were active sodium monofluorophosphate, inactive dicalcium phosphate dehydrate, water, glycerine, sodium lauryl sulfate, cellulose gum, flavor, tetrasodium pyrophosphate, and sodium saccharin. The paint tested was a nontoxic, water based paint used for children. The ingredient in the petroleum jelly was white petrolatum USP, and is an important component in many ointments and creams.

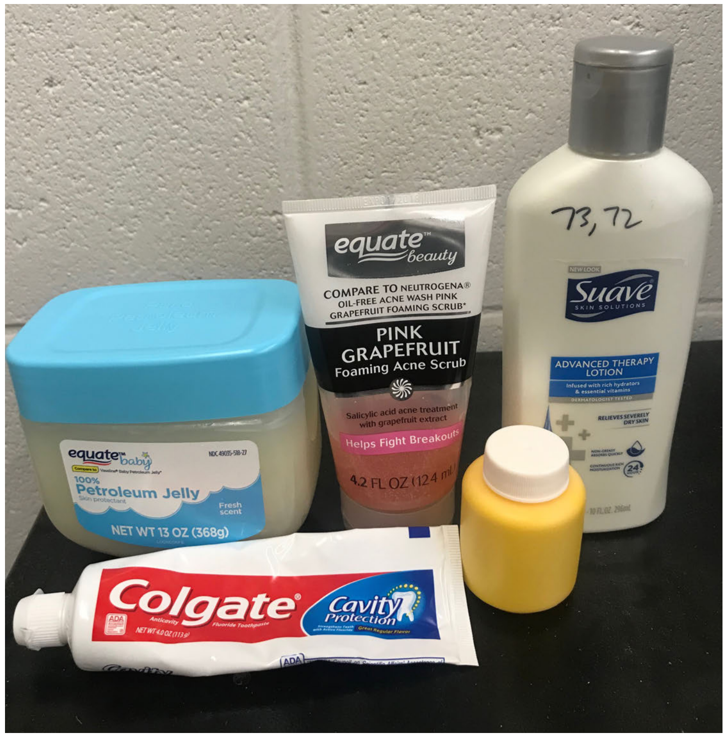


Image 6: The everyday products that were measured

PEG 750 is almost solid at room temperature and resembles the properties of wax or petroleum jelly. Because this polymer is so thick, the rheometer was not able to measure the yield stress. However, other data, including stress, strain, and torque at given times, were still collected. On the other hand, PEG 350 is very fluid and offered little to no initial resistance to flow.

The two different brands of mayonnaise used for comparison were very similar. The ingredients of Hellmann's mayonnaise were soybean oil, water, whole eggs and egg yolks, vinegar, salt, sugar, lemon juice, calcium, Disodium EDTA. Kroger brand mayonnaise included the same ingredients but in a different proportion. The nutritional values of the two were also comparable with Hellmann's having 90 food calories and 90mg of sodium per tablespoon. With slightly higher values, the

Kroger brand mayonnaise had 100 food calories and 95mg of sodium per tablespoon. Their yield stress values are recorded in the Results and Discussion section.

Image 7: The comparable mayonnaise brands

After using the DV-III Rheometer and the EZ Yield program to collect data, Logger Pro was used to represent this data in graphs (13).

RESULTS AND DISCUSSION

Most of the products measured had to use the 73 vane spindle, and a comparison of their results are below.

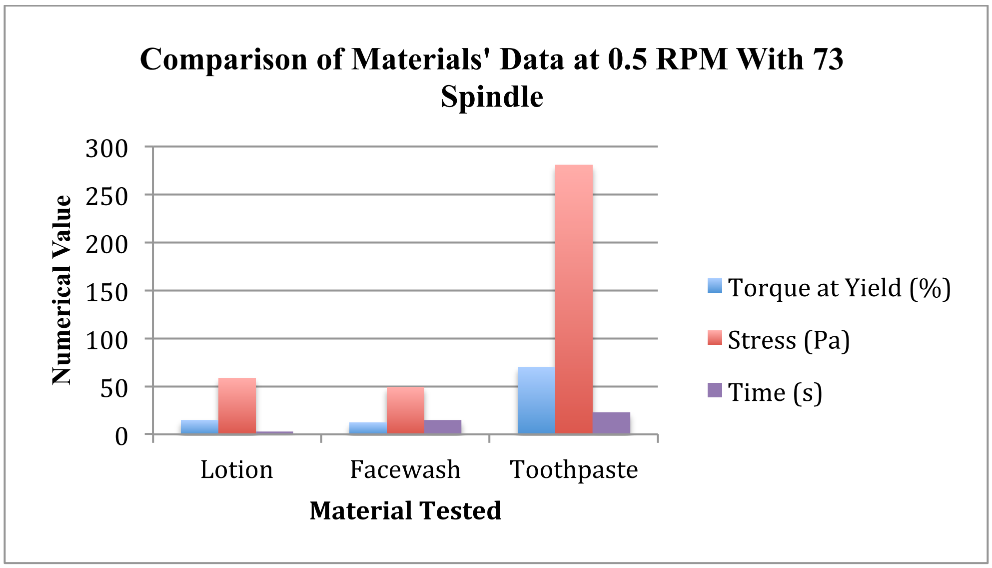


Figure 1: Spindle 73 data. Torque, yield stress, and time of materials measured with 73 spindle at speed of 0.5 RPM.

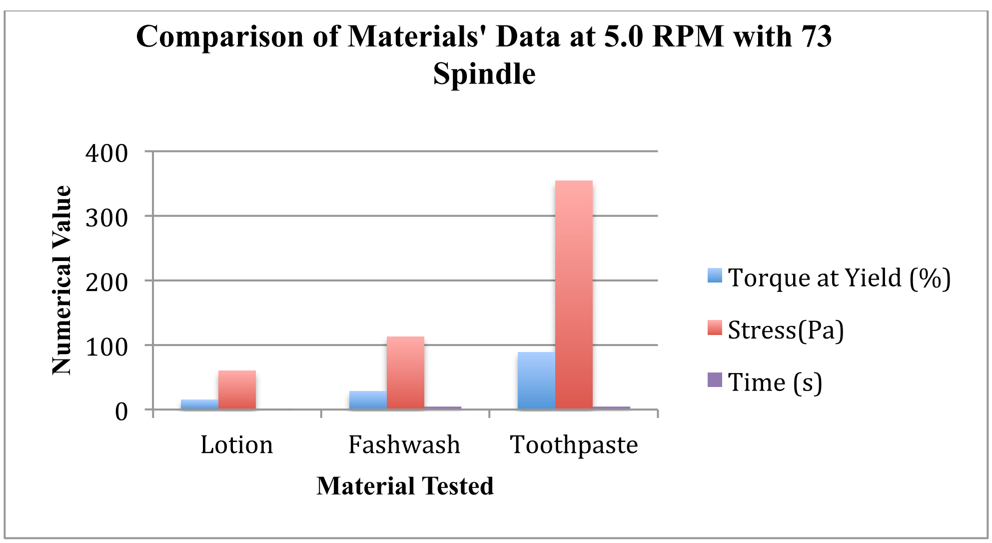


Figure 2: Spindle 73 data. Torque, yield stress, and time of samples measured with the 73 spindle at a speed of 5.0 RPM.

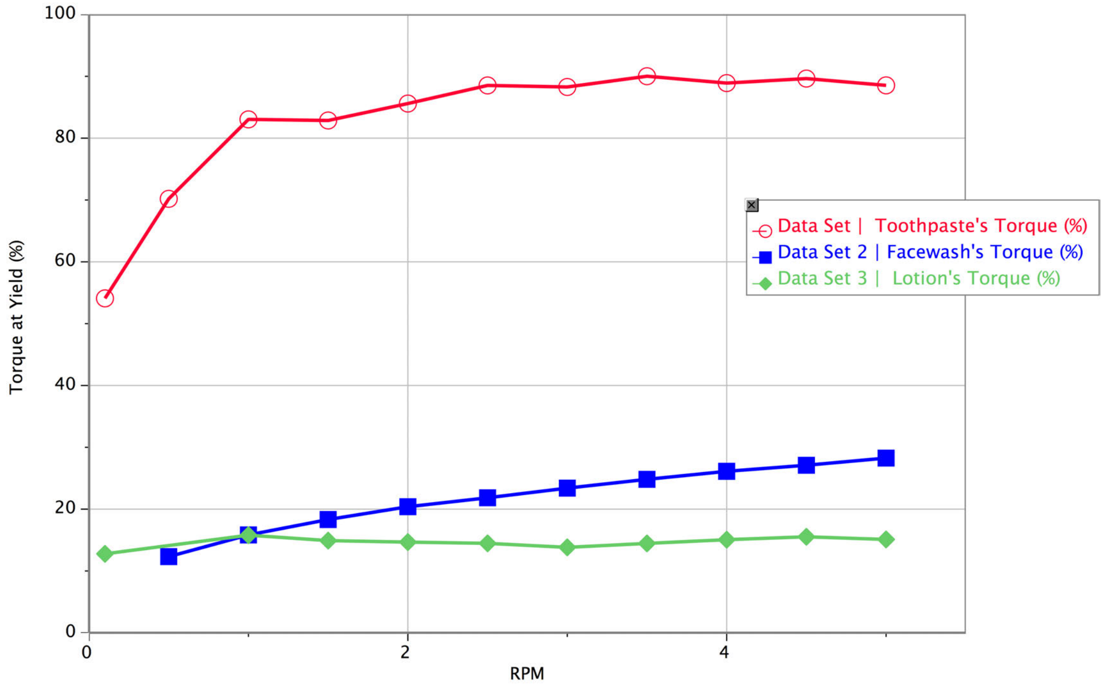


Figure 3: Torque Comparison. This graph shows the Torque at Yield of each speed. The red represents toothpaste, the blue is facewash, and the green is lotion. Spindle 73 was used with all of these samples.

From the above graphs, it is seen that the toothpaste has the largest value in every category, especially its Stress measurement. This measurement means that toothpaste requires the most force to initiate flow, followed by the facewash, then the lotion. By looking at both Figure 1 and Figure 2, it is shown that the rotational speed of the spindle does not alter the comparison of the different products. In Figure 3, the facewash and the lotion start off with similar torque values. However, as speed increases, the facewash receives more torque and the lotion's torque remains relatively constant. This value is, in part, attributed to the microbeads in the fashwash, which present more force against the spindle because of its heterogeneous phase.

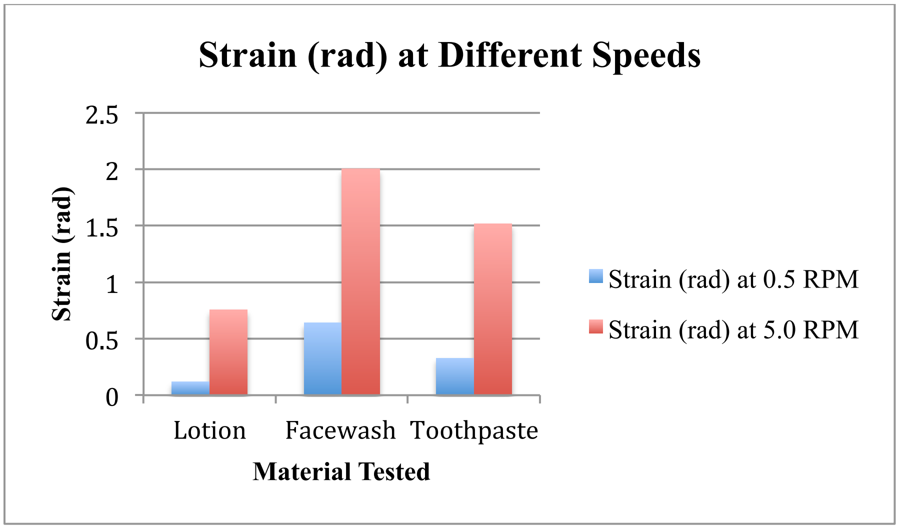


Figure 4: Strain Comparison. This chart compares the strain values at speeds of 0.5 RPM (blue) and 5.0 RPM (red).

In Figure 4, it is seen that the facewash actually has the most strain compared to the toothpaste and the lotion. Strain can provide the rate of deformation of a sample undergoing force. Because the facewash contains microbeads, the sample's texture is not as homogeneous as the toothpaste and the lotion, and the rotation causes the facewash to change shape at a greater magnitude. The solid particles cause the gel to have a greater deformation rate, which also increases with speed. The strain of each product increases with speed because of the greater force that causes shape deformation.

Both the yield stress and the percent torque at the yield stress generally increase with increasing speed. Sometimes these values may slightly decrease after reaching a certain value or if the test has surpassed the yield stress value.

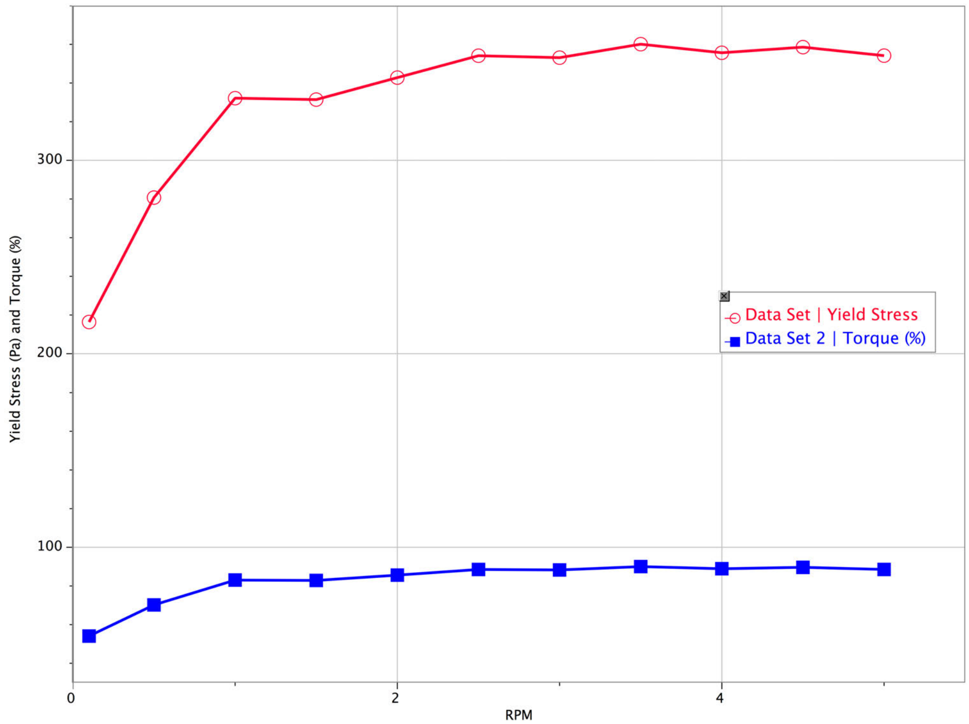


Figure 5: Toothpaste Comparison. Yield stress values (red) and Torque (blue) values of toothpaste with increasing speed using spindle 73.

Figure 5 shows similar trends of torque and yield stress. While the values of yield stress are much greater than those of torque, the slope of the two lines are very similar, and the later values both result in an horizontal line. The horizontal line indicates that there is little difference between the values at increasing speeds because the substance no longer requires as much force to initiate flow.

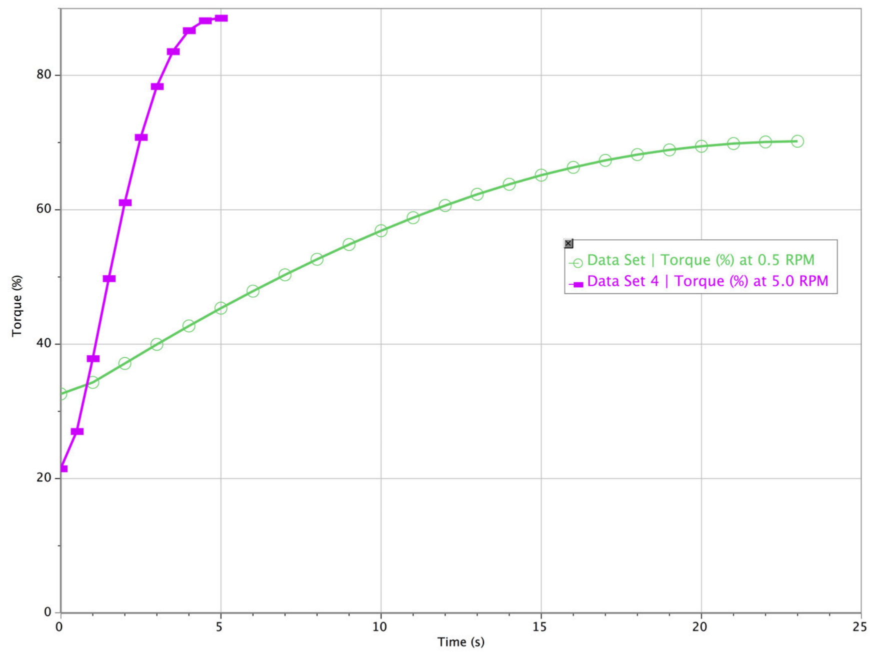


Figure 6: Torque at different speeds. The purple line represents the torque percentage of toothpaste at 5.0 RPM, and the green line shows the torque percentage at 0.5 RPM over time.

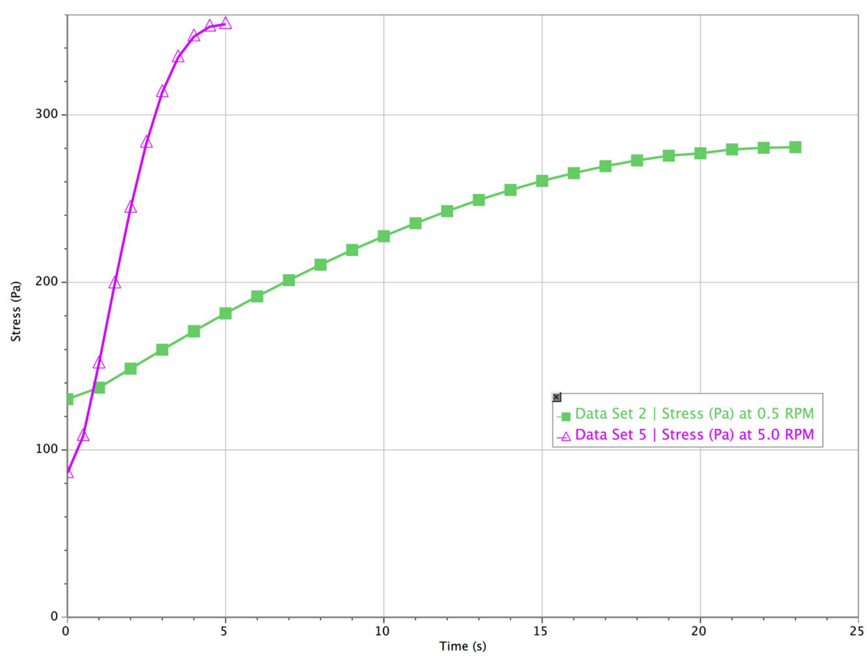


Figure 7: Stress at different speeds. The green line shows the stress (Pa) of toothpaste at 0.5 RPM, and the purple line represents the stress of toothpaste at 5.0 RPM with increasing time.

Again we see similar trends between the torque and stress values in Figures 6 and 7. Increasing the speed of the spindle causes the torque to increase at a faster rate and to higher values because the greater force acting on the sample. The difference between torque values, or delta torque, begins to diminish as it approaches the yield stress value, or the final stress measurement. In Figure 6, the line showing the faster speed has a much steeper slope than the line representing the slower speed. Similarly, Figure 7, shows how increasing the speed results in an increase of stress within a shorter period of time.

In Figures 6 and 7, the lines representing a speed of 5.0 RPM do not continue past 6 seconds because after the Yield stress is obtained, there is no more great changes in Stress with increasing Torque. If these lines were to continue, they would plateau. Depending on the substance, the line may eventually slope downward due to a fracture in the substance. The initial increase of torque is due to the greater resistance the material exhibits right when the force is applied. Once a certain amount of force is present, the torque begins to decrease because the sample does not have as much resistance to flow.

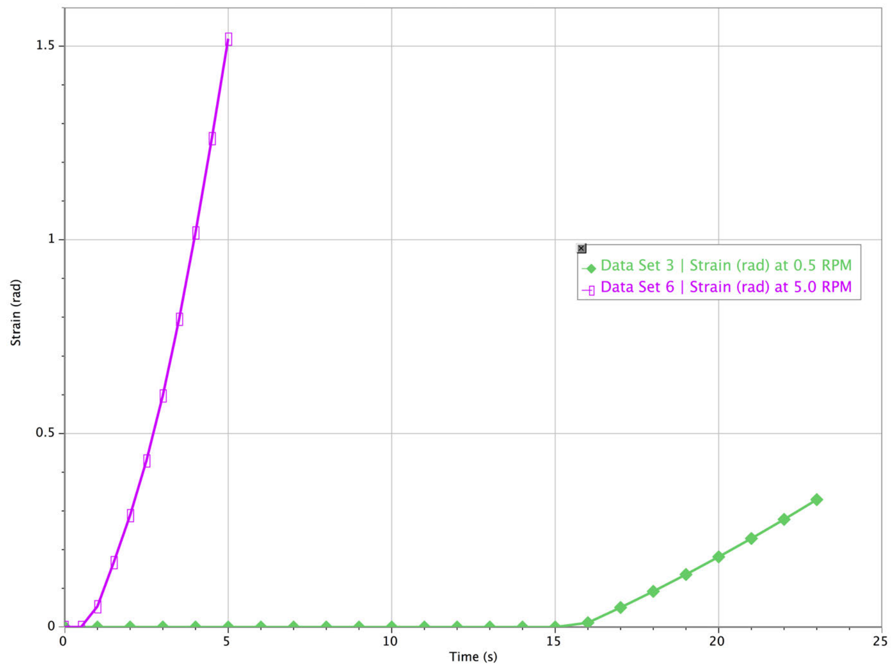


Figure 8: The purple line represents the strain (rad) of toothpaste at 5.0 RPM, and the green line shows the stain of toothpaste at 0.5 RPM with increasing time.

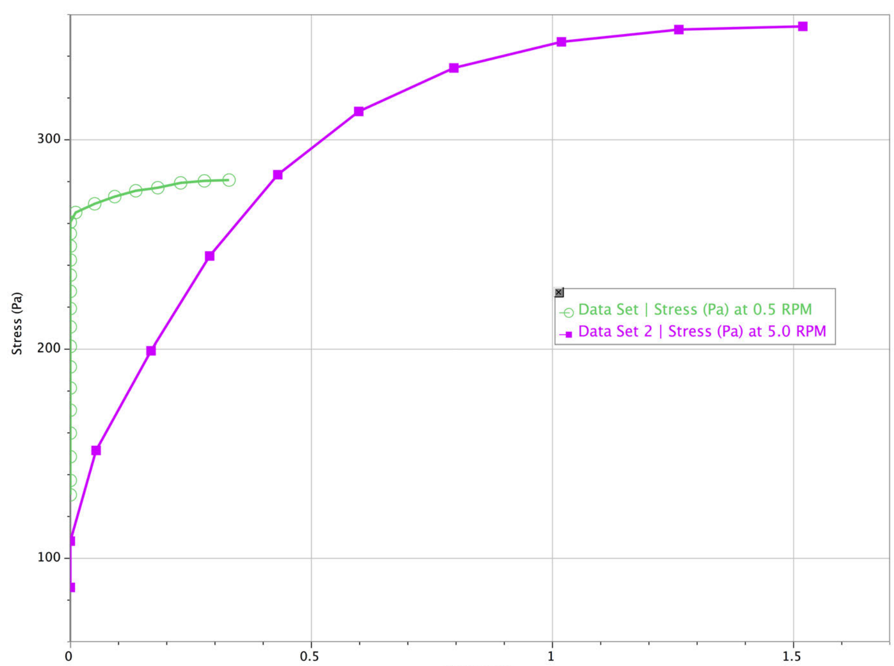


Figure 9: Stress vs. Strain of Toothpaste. This graph shows the stress (Pa) of toothpaste verses the Strain (rad) at 0.5 RPM (green) and 5.0 RPM (purple).

Strain remains zero until there is enough torque to change shape. Because speed increases torque, speed also increased the strain on a sample. In figure 8, the faster speed experiences much higher strain values in less than half the time it takes the slower speed to reach its maximum strain. The slopes of these two lines also vary in that the slope is smaller and takes a linear shape. The faster speed resembles an exponential growth curve with increasing slope. Figure 9 compares graphs of stress versus strain at different speeds. The faster speed reaches its yield stress value in almost a fifth of the time that it took the slower speed to do. The slope of the faster speed decreases slowly until it approaches a slope of zero, while the slower speed goes from vertical to almost directly into zero slope, resembling a right angle. This trend is due to the lack of strain on the sample because of the slow speed. Both of the lines end in a slope around zero, which indicates that the yield stress values was obtained. The point on the stress verses strain curves that begins to shift the slope to a horizontal line is the Yield point. This point refers to the elastic yield, which means it is the last point that the sample's deformation will go back to its original shape once the force is no longer applied. Beyond this point, the sample will undergo deformation that will remain even after the force it removed (7).

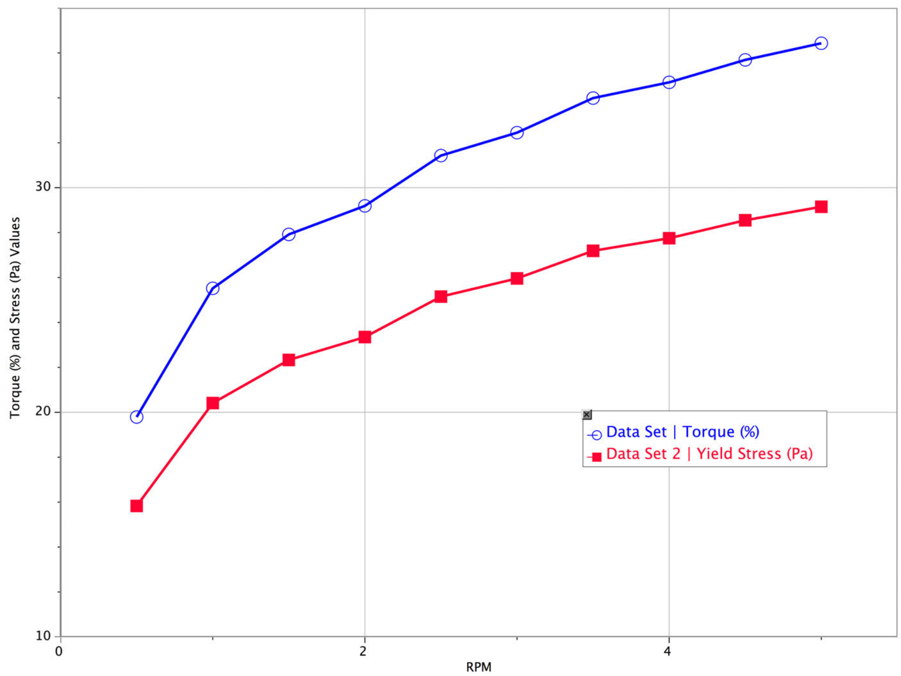


Figure 10: Paint Data. The blue line shows the torque percent of paint with increasing speed, and the red line represents the Yield stress at each speed. The paint used spindle 72.

Because the paint did not require much force to experience flow, spindle 72 had to be used; thus, this sample could not be graphed with the other samples. However, the same trends still apply as seen in Figure 10 by the similar shapes of the torque and yield stress curves.

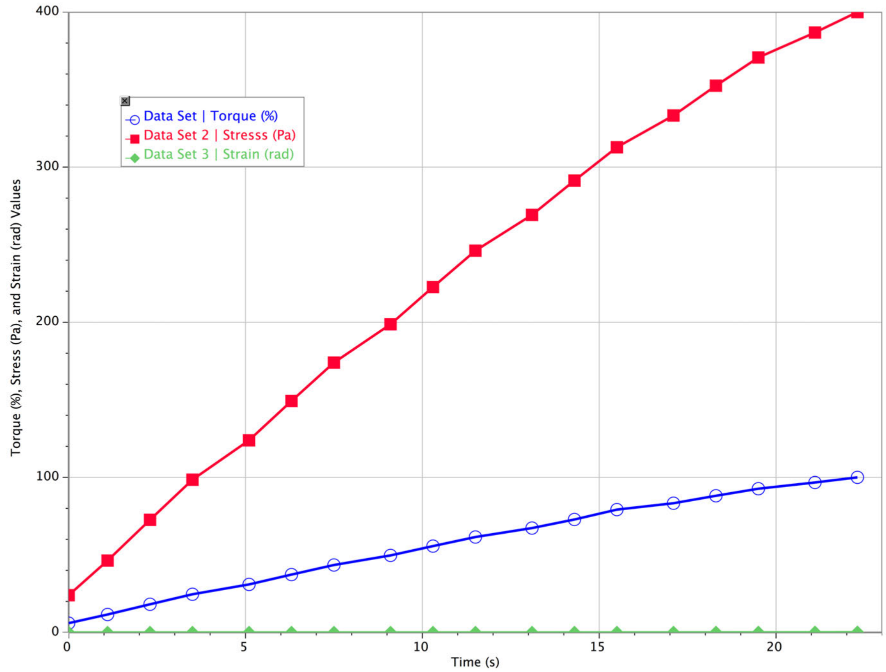


Figure 11: This graph shows the torque (blue), stress (red), and strain (green) of petroleum jelly at 0.01 RPM with increasing time. The yield stress value is the final stress reading, which is 399.96 rad. Spindle 73 was used, and this was the only speed that could collect a yield stress due to over range failure.

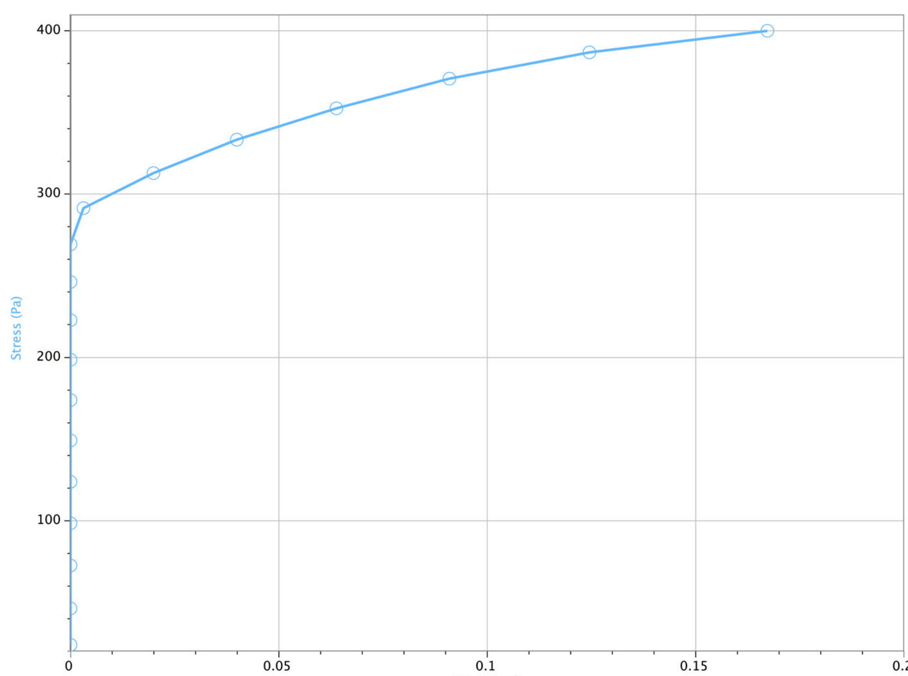


Figure 12: Petroleum Jelly Data. This graph is the stress (Pa) of petroleum jelly versus the strain (rad) over time at a speed of 0.01 RPM.

Petroleum jelly is considered a semi-solid material, making it unique when measuring its stress, strain, and torque values. At room temperature, petroleum jelly does not exhibit a constant flow because of its extremely viscous and consistent texture. The Stress versus Strain of petroleum jelly has a yield point early on, indicating that even a slight force can lead to permanent shape change in the subject until another force acts on the sample.

Viscosity of Polyethylene Glycol Samples

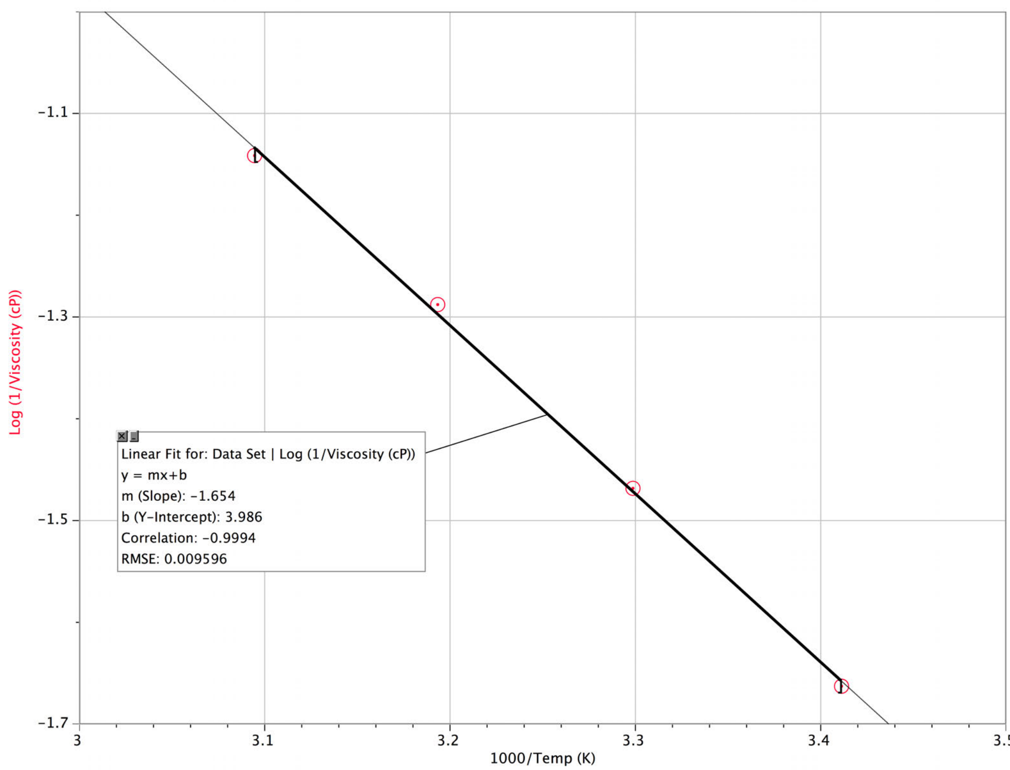


Figure 13: Fluidity of PEG 350. This graph shows the activation energy of fluidity of PEG 350 versus increasing temperature. The temperature, which is on the X-axis, is one thousand divided by the temperature in Kelvins. The Y-axis is the log of the inverse of viscosity.

Viscosity values decrease and fluidity increases with increasing temperature, which is why substances flow faster at hotter temperatures. Figure 13 shows Arrhenius activation of fluidity with temperature. The X-axis is the inverse of temperature, where the temperature decreases from left to right. The Y-axis is the log of viscosity, where the viscosity increases as you go down the Y-axis. The negative slope shows the increase of PEG 350's viscosity as the temperature cools or decreases. Viscosity is important in determining yield stress because the more viscous a material, the more force is required to initiate flow, making it have a higher yield stress value.

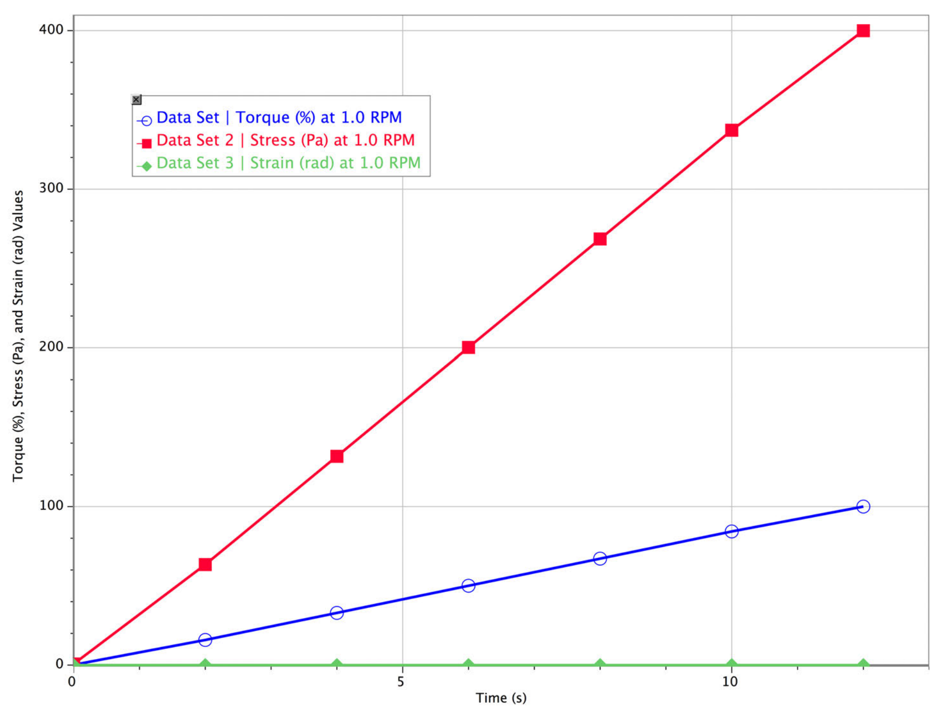


Figure 14: PEG 750 Data. The yield stress test for PEG 750 failed because it was over range. This graph shows the strain (green), stress (red), and torque (blue) of PEG 750 at a speed of 1.0 RPM over time. These readings are very similar petroleum jelly's data.

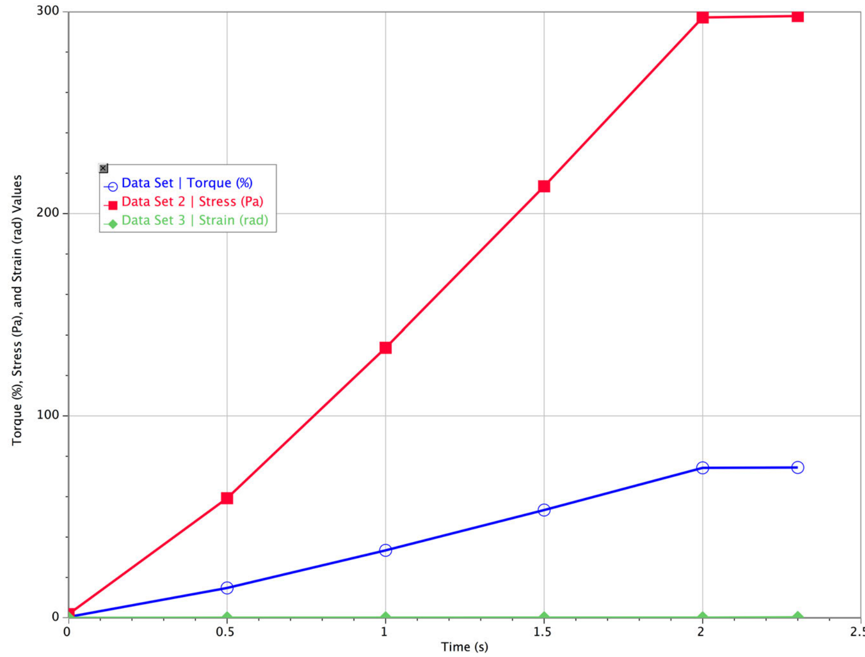


Figure 15: PEG 750 Data. The yield stress test for PEG 750 failed because it was over range. This graph shows the strain (green), stress (red), and torque (blue) of PEG 750 at a speed of 5.0 RPM over time.

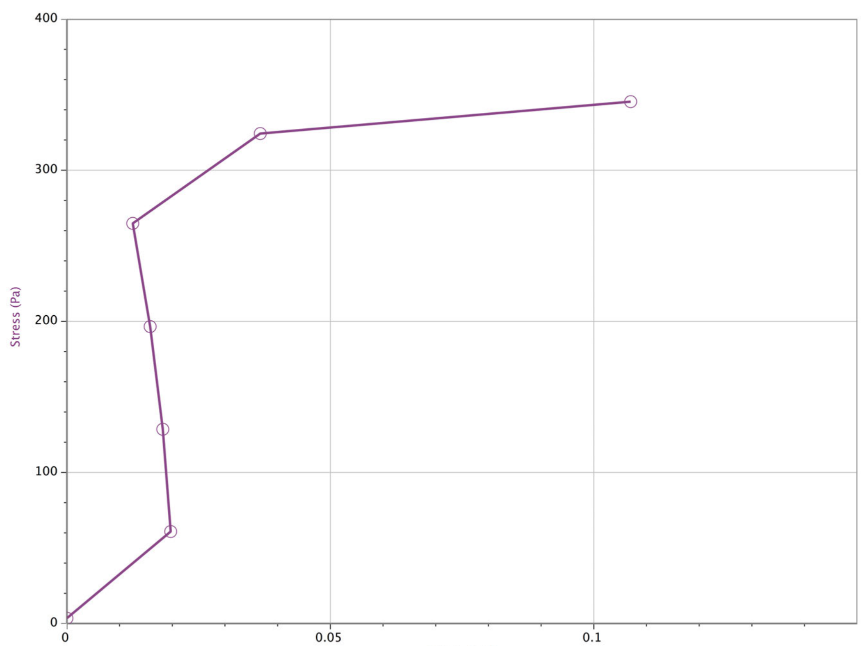


Figure 16: Stress vs. Strain of PEG. This graph shows the stress (Pa) of PEG 750 verses the strain (rad) at a speed of 0.5 RPM. This test did not pass the yield stress test due to over range, and spindle 73 was used.

The data in Figure 15 is taken from a yield stress test that failed due to over range. One aspect that reveals this failure is the linear shape of all the lines. In a test where the yield stress is able to be obtained, the torque values tend to get closer together as it approaches the final value, but in this graph the difference in torque continues to increases linearly. PEG 750 demonstrates thixotropic properties, meaning as more stress is applied, the material becomes more inclines to change structure and flow (11). Towards the end of the torque line in Figure 15, the value stops increasing because the sample begins losing some resistance. Figure 16 shows the stress verses strain of PEG750, but the curve does not follow a typical model. Because this polymer is so thick at room temperature, it is hard to initiate any flow, much less a consistent flow. This graph should determine when the material goes from elastic deformation to a permanent deformation, but there are too many slopes changes. When the spindle rotated within the PEG 750 sample, air pockets would become trapped within the sample resulting in non-uniform shape changes. This shape explains the many different, permanent, deformations PEG 750 undergoes with any force acting on it.

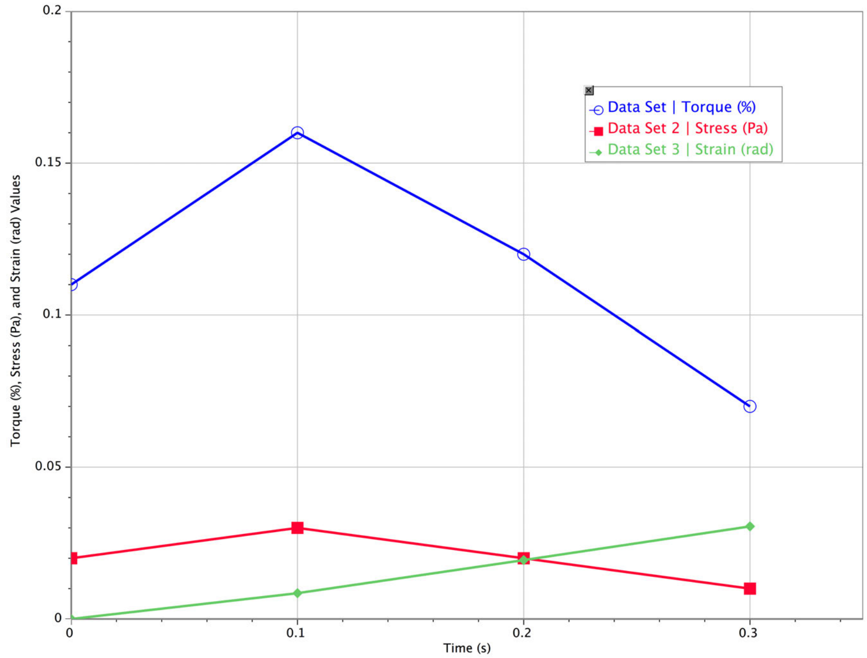


Figure 17: Failed PEG 350 Test. This test failed due to under-range conditions. The graph shows data of PEG 350 at a speed of 1.0 RPM. The green line shows the strain, the red line represents the stress, and the blue line shows is torque. Spindle 71 was used.

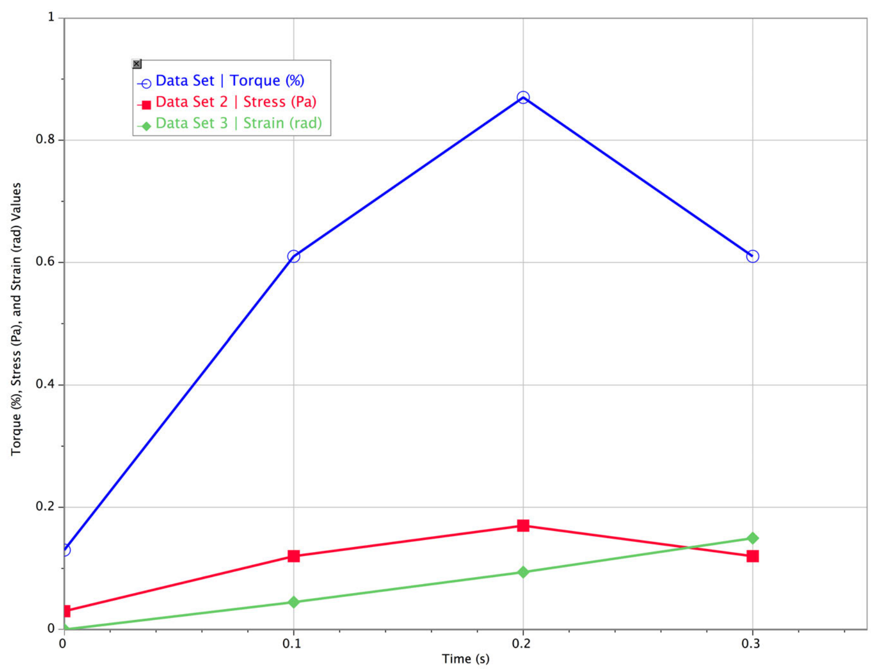


Figure 18: PEG 350 Data. This graph shows the under-range data of PEG 350 at a speed of 5.0 RPM. The green line shows the strain, the red line represents the stress, and the blue line shows is torque. Spindle 71 was used.

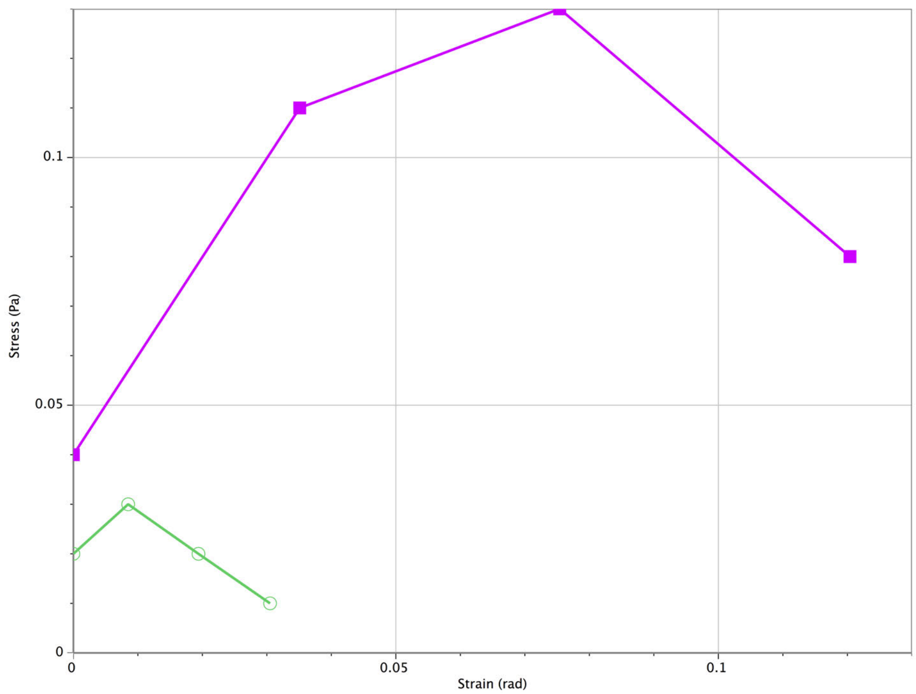


Figure 19: PEG 350 stress. This is a graph of the stress (Pa) of PEG 350 versus the strain (rad) at speeds of 1.0 RPM (green) and 5.0 RPM (purple). These yield stress tests failed because they were under range, and spindle 71 was used.

Failure of a yield stress test due to under-range conditions is usually because the substance is too fluid, the spindle is too small, or the speed is too slow. PEG 350's failure can be attributed to the first reason because it does not require much energy for it to flow. Figure 18 shows the negative slope of PEG 350's torque and stress lines, which exemplifies the failure of this test by showing that the sample does not offer enough resistance to flow. Another factor of this graph that points to its failure is the extremely short period of time it took, which was 0.3 seconds. Although the speed varies, Figures 17 and 18 show almost the exact same slope of the lines but at different numerical values. In successful Yield Stress tests, the stress versus strain graphs favor that of a logarithmic growth plot. However, in Figure 19, the representations of both speeds result in a negative slope. This negative slope indicates that this sample will not undergo (or will experience the slightest) deformation.

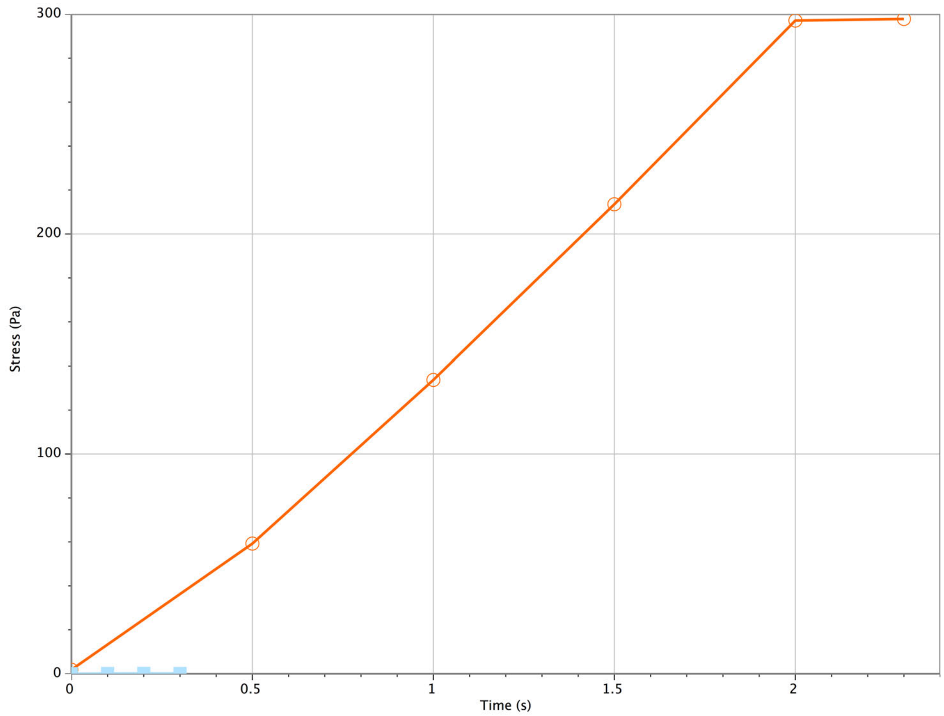
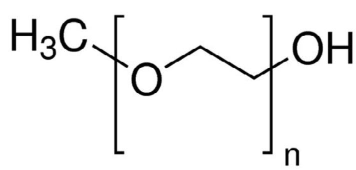


Figure 20: PEG Comparison. This graph shows the vast difference of the stress values of PEG 350 (light blue) and PEG 750 (orange) at a speed of 5.0 RPM versus time.



Structure 1: Polyethylene glycol molecular structure (10)

While both of the samples tested in Figure 20 are Polyethylene glycol polymers, the varying versions have much different properties. Structure 1 shows the molecular structure of PEG, where “n” stands for the number of units present in the polymer. Changing “n” results in polymers of different molecular weights (10). While running EZ Yield, PEG 350 was too fluid to result in Stress values, and PEG 750 received too much stress because of its partially crystalline structure. Although yield stress values could not be read on these tests, other data was helpful in evaluating the samples' properties.

Brand Comparison of Mayonnaise

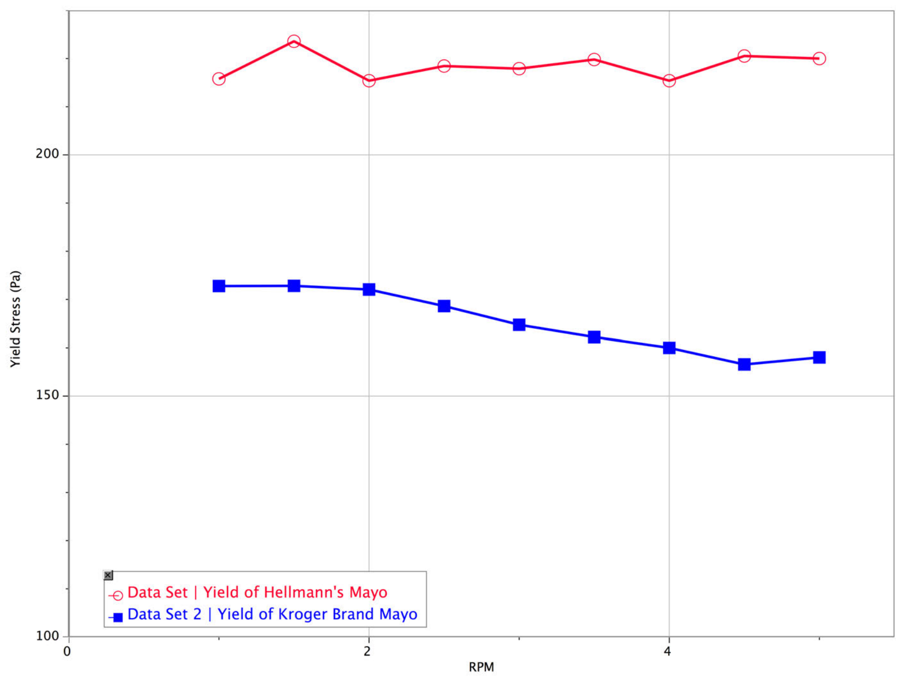


Figure 21: Brand comparison. Blue is Kroger and red is Hellmann's mayonnaise

Yield stress analysis can be used to test similar products or to compare different brands of products that contain slightly different ingredients. Without measurement, similar products may appear to have little differences, but yield stress analysis can reveal varying properties. Figure 21 shows the yield stress values of Hellmann's mayonnaise (red) and Kroger brand mayonnaise, which both act as soft solids. Their values are not drastically different but the Hellman's brand shows higher stress due to a more resistant texture. Hellmann's brand also contains less calories and sodium, and it has an airier texture than the mayonnaise from Kroger. A reason for the higher stress and torque values of Hellmann's product is due to the different proportion of ingredients. Mayonnaise is a complex structure, consisting of fats, which normally resist mixture. This emulsified sauce overcomes separation through specific instructions and ratio of ingredients at different temperature in order to create the viscous substance. By reducing the size of the droplets in an emulsion, the mixture will become more stable and less likely to separate. This technique is used when making mayonnaise, and if done incorrectly the product will curdle or separate. Egg yolks, which are a key ingredient in mayonnaise, contain a fat emulsifier called lecithin that stabilizes the product (1). Mayonnaise, because of its semi-solid complexity, provides a great example of yield stress measurement and comparison.

Yield stress can influence laminar flow within a container, which is parallel flow that does not exhibit deviation from each layer (8). In this scenario, yield stress is important in canning food, mixing ingredients of different properties, pumping materials through a series of pipes, or coating products with liquid like substances. All of these steps are crucial when manufacturing goods, and exemplifies the importance of yield stress in our day-to-day lives.

Some products do not get a yield stress reading when using the equipment in this study. One reason for this failure is due to an under-range condition. An example is PEG 350, which is a more fluid and easily flowing substance. An under-range result occurs when the substance begins to flow before the torque value reaches 10%, and the program cannot give a final value. An over range condition also results in a test failure. Petroleum Jelly was too thick and would change its shape when force was applied. Only the test with the lowest speed with the smallest spindle was able to get a Yield Stress value from this sample. In the case of over range, the yield stress is not reached by the time the torque arrives at 100%.

Another property that yield stress can lead to is the ability of a substance to absorb energy. At higher temperatures, a substance processes a higher energy due to thermal energy absorbed (14). Because of this force already applied to the sample, not as much applied force is needed to initiate flow. In other words, the yield stress decreases with increasing temperature because the thermal energy has already contributed to the initiation of flow and the elastic area does not absorb as much energy (4). This idea explains why the viscosity decreases with increasing temperature and is thus, more fluid.

Before a material reaches its elastic limit, resilience is used to describe its ability to absorb energy and is recoverable. Studies of resilience have lead to important breakthroughs in cleaner, reusable energy sources (14). The energy that a material can absorb after the yield point is generally greater than the elastic energy.

Related to yield stress, is the yield point. The elastic limit occurs when a product starts behaving as a plastic and is shown as a non-linear graph. When a substance reaches its elastic limit it is refereed to as its yield point, in which plastic deformation begins (6). Elastic deformation allows the product to reform back into its original shape once the force is no longer applied. Once plastic deformation is reached, the sample will not return to its original structure, but will instead undergo permanent deformation until another force acts on it. The yield point can be observed on a Stress versus Strain curve as the point where the curve begins to level out (7). This curve is also reveals the Fracture Point, which is seen on the curve once the peak has been reached and the graph has a negative slope. Because no solid objects were used in this study, no fracture points are represented on the Stress verses Strain graphs.

CONCLUSION

Analyzing the Yield Stress of a sample can provide the elastic and plastic properties, the amount of force needed to initiate flow, the strength of its structure, and other properties useful for manufacturers. While this value determines the solid properties of a sample, viscosity measures the liquid properties of a sample.

There are still debates over the accuracy and relevance of yield stress, as well as the best method to complete these measurements. Overall, the characteristics of a sample determine the best method of measurement. With the DV-III Rheometer and EZ Yield software, it was determined that soft solids or semi-liquids were the best samples to get yield stress values.

Graphing the collected data on a Stress verses Strain plot provides many useful measurements, including the amount of elastic energy and plastic energy, which describes the deformation patterns. Knowing the deformation rate allows manufactures to account for the correct packaging, transporting, piping, spreading, and mixing mechanisms used for their products.

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